Report

Combustion scaling laws and inlet starting for Mach 8 inlet-injection radical farming scramjets

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Summary

This project has investigated **the fundamental scaling laws for supersonic combustion in scramjets flying at Mach 8**. Developing these laws is critical for successfully transitioning small-scale ground test and flight experiment data to the design of full-scale scramjet vehicles. To achieve this, the project has employed state-of-the-art diagnostics to investigate inlet-injection radical farming supersonic combustion in a shock tunnel over a wide range of dynamic pressures at flight Mach 8. The particular configuration is the two dimensional analogue of the axisymmetric scramjet intended for HIFiRE 3 – one of ten flight experiments in the current HIFiRE program that is building on previous successful HyShot flights at Woomera (Figure 1). The project provides important fundamental science to underpin the radical farming technology to be employed in three of the HIFiRE flights (3, 7 & 8).

The project has also employed time-accurate Navier-Stokes computational fluid dynamics (CFD) to investigate several proposed methods for starting the high contraction ratio inlet of the axisymmetric configuration. This is of critical importance for the HIFiRE 3 flight.

Figure 1. The HyShot IV captive-carry rocket-launched scramjet flight experiment. HIFiRE will employ the same approach.

The specific aims of the project have been to develop scaling laws for supersonic combustion by

- directly measuring surface pressure and heat transfer in a fundamental inlet-injection radical farming scramjet configuration in the T4 hypersonics shock tunnel at UQ, at flight Mach 8 enthalpy, over the range of freestream dynamic pressures 40-200 kPa
- support these measurements with spatially accurate imaging of the OH radical formation in the ignition process, via Planar Laser-Induced Fluorescence (PLIF) imaging

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- couple to the experimental results computational fluid dynamics simulations and combustion kinetics analyses, to provide detailed understanding of the coupling between the flow structures and the combustion chemistry
- validate (or not) the application of p*L binary scaling to the radical farming class of scramjets to enable extrapolation of ground test data to flight configuration design

The specific aim to investigate inlet starting for this class of high contraction ratio (axisymmetric) scramjet was to

- employ time-accurate Navier-Stokes CFD simulations to investigate the viability of four separate methods for starting the inlet – opening doors, eroding conical diaphragms, tractor inlet plug rockets, and inlet gas injection.

Background.

Australia and the United States are currently conducting the joint HIFiRE fundamental hypersonic flight experiment program. HIFiRE is a US$50M program between the two major partners, Australia's Defence Science and Technology Organisation (DSTO) and the USAF Research Laboratories (AFRL), but includes significant participation from the world's leading university-based hypersonics research group at The University of Queensland, and significant funding from the Queensland State Government through their Smart State funding initiative.

The aim of HIFiRE is to undertake fundamental in-flight research of hypersonic phenomena using the sounding rocket technology that has been employed in the successful HyShot scramjet flight experiments (see Figure 1). The phenomena which are of interest are those which are most critical to hypersonic airbreathing propulsion. Ten flights are to be conducted, at the Woomera Test Range in South Australia. The first two, HIFiRE flights 0 and 1, are on track for launch in November 2008. The program includes the necessary ground testing and computational fluid dynamics (CFD) simulations needed for designing and analysing the flight experiments.

In HIFiRE, two main airbreathing concepts are being considered : the dual-mode combustion ramjet/ scramjet typically investigated by USA and European agencies for lower flight speeds (Mach 5-7), and the Rectangular-to-Elliptical-Shape-Transition (REST) engines (Smart, 1999) under development at UQ. The REST concept in particular is demonstrating excellent thrust performance in shock tunnel ground tests. The final two HIFiRE flights will seek to determine the thrust performance of free-flying REST (flight 8) and dual-mode (flight 9) engines at Mach 8.

Figure 2. The 2D inlet-injection radical farming supersonic combustion configuration of Odam & Paull (2007).

However, a third concept is also under investigation in HIFiRE – a simple axisymmetric configuration (circular cross-section inlet, combustor and thrust nozzle) with inlet-fuel-injection – and is intended to form the payload for HIFiRE flight 3. The purpose for including this concept is to provide fundamental flight data in a simple generic configuration for the inlet-fuel-injection “radical farming” supersonic combustion concept that has shown potential in Australian shock tunnel studies and is of considerable interest here (Odam & Paull, 2007; McGuire et al, 2007, 2008a, 2008b). As shown in Figure 2, in the two-dimensional configuration employed by Odam & Paull (2007), fuel is injected from portholes in the inlet rather than in the combustion chamber, enabling fuel/air mixing to occur upstream of the combustor, reducing model lengths and thus skin friction drag. The hot pockets that are part of the complex flow structure in the combustor then generate the radical species necessary for ignition and heat release – hence the term “radical farming”. It is important to note that significant combustion heat release has been achieved with this technique even when the mean combustor entry conditions are too mild for ignition. Ignition and heat release are obtained by correctly coupling the finite-rate combustion chemistry, which depends on the local temperature, pressure and fuel/air mixture, with the localized hot flow structures. Critical to this is the residence time as the fuel/air mixture passes through these hot pockets, and in turn the number and size of these structures is also critical. A large-scale configuration, with larger hot pockets, should not need as many as a small-scale configuration. With this scramjet concept, both the inlet contraction ratio (and its associated drag and total pressure losses), and combustor length (and associated skin friction drag) can be reduced, while still achieving heat release within the combustor. Furthermore, combustion is initiated at lower temperatures, leading to higher thrust. The HIFiRE 3 configuration proposed is the **axisymmetric** equivalent of the 2D configuration shown in Figure 2 and, as stated above, has been intended to provide fundamental flight data for the inlet-injection radical farming approach.

There is strong motivation for applying such an axisymmetric concept to an actual commercial platform – unlike the REST concept, being axisymmetric the configuration is extremely simple in shape, is fundamentally very strong per unit mass, suffers none of the extreme localised heat loads suffered by asymmetric concepts such as REST, and has the minimum skin friction drag of any possible configuration. Thus it is relatively simple and inexpensive to design and manufacture, and therefore has enormous potential for successful commercialisation, if it can be demonstrated to possess sufficient performance and if issues associated with starting the engine are overcome.

Small-scale shock tunnel ground tests of this axisymmetric configuration have been performed recently by Hunt, Paull and Boyce. The configuration can be seen in the photograph and numerical simulation provided in Figures 3 and 4, while Figure 5 shows sample results of the combustion-induced pressure rise in the combustion chamber and in particular in the thrust nozzle in these tests. The discrete hot (and high pressure) structures in the combustion chamber in the fuel-off case are evident in both Figures 4 and 5. In the fuel-on case shown in Figure 5, at a fuel-air equivalence ratio of 0.7, two hot pockets have been needed to generate radicals and achieve ignition heat release for this particular contraction ratio (6.7). Experimental work has also been performed to determine whether lower contraction ratios will also achieve ignition, and if so how many hot pockets are required at this small engine scale. Importantly, the results to date at the high contraction ratio have shown significantly higher levels of combustion energy release without choking the engine than was previously thought possible – in fact, performance levels are similar to the REST concept. The lower contraction ratio investigated has also successfully achieved ignition. This simple inlet-injection radical farming axisymmetric configuration offers enormous promise.

Figure 3. The baseline (HIFiRE 3) axisymmetric configuration
in the T4 shock tunnel at UQ – view from upstream.

However, further fundamental research into the fundamental science that underpins this class of scramjet has been needed before the configuration can be realised in practice. In particular,

- the manner in which such inlet-injection supersonic combustion scales as the size of the configuration is scaled must be determined, and
- methods to start the high contraction ratio axisymmetric inlet must be investigated

These are the focus of the research conducted here.

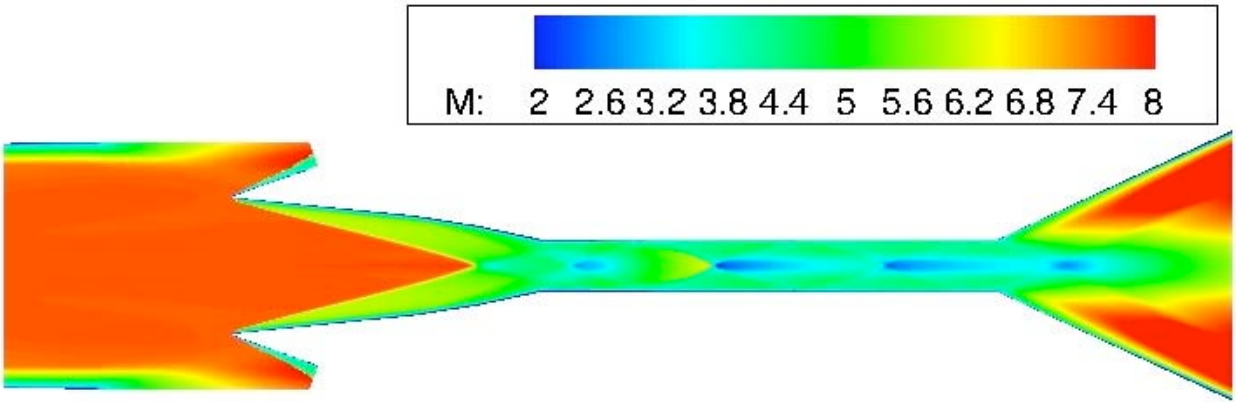


Figure 4. Mach number contours from a numerical simulation of the baseline configuration outside the exit of the Mach 7.6 nozzle in the T4 shock tunnel (fuel-off case).

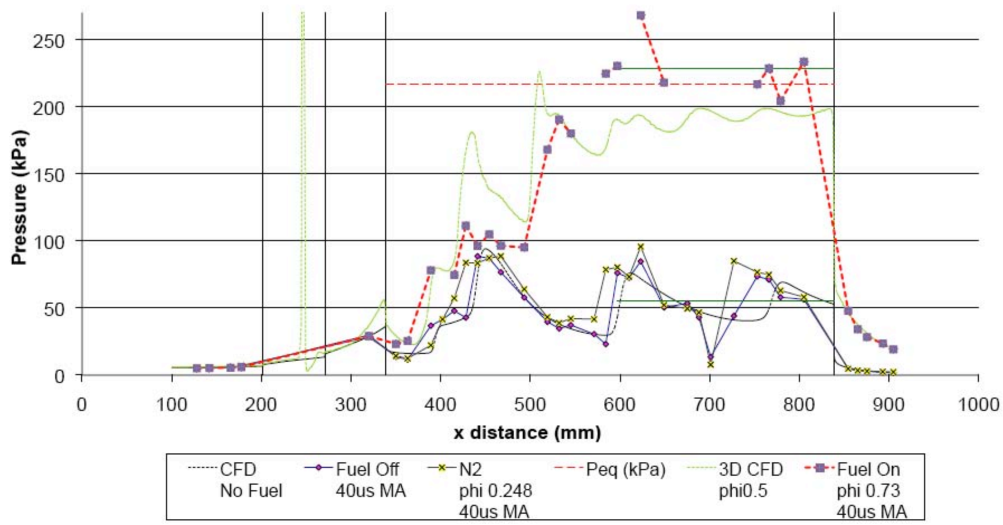


Figure 5. Pressure distributions through the baseline configuration in the T4 shock tunnel, displaying supersonic combustion and radical farm behaviour. Chart provided by Mr Dillon Hunt
(UQ PhD student and DSTO Applied Hypersonics Senior Mission Systems Engineer).

Supersonic combustion scaling.

For ground-based research of scramjet configurations to be relevant to practical scramjet vehicle designs, it is critical to understand the way in which supersonic combustion flows scale from the laboratory to flight. This is necessary because generating net thrust, or at least no net drag, will depend on minimizing the combustion chamber length so that skin friction drag and structural weight are minimized, while ensuring that the combustor length is sufficient for achieving maximum heat release.

Previously, supersonic combustion scaling research was conducted by Stalker et al (2005) at hypervelocity enthalpies equivalent to flight Mach 10-15 in the T4 shock tunnel at UQ. That work employed central strut injection of H_2 into parallel hot air streams, for which combustion reactions can proceed in a continuous manner rather than in the stop-start fashion dictated by propagation through local hot flow structures. Stalker et al showed for both mixing-controlled and reaction-controlled combustion that the product pressure*length (*p*L*) was the appropriate scaling parameter in that scenario. p*L scaling is essentially binary scaling, applicable to the situation where two-body dissociation reactions dominate three-body recombination reactions. In other words, small-scale ground tests of combustion in a central strut injection engine with hot combustor entry conditions can be extrapolated to full-scale flight configuration design by ensuring that the ground test results conserve the flight vehicle p*L value.

Is this also the case for inlet-injection radical farming configurations? As discussed earlier, this class of scramjet seeks to establish combustion with mild mean combustor entry conditions, using the accumulated exposure of the fuel/air mixture to discrete localized flow structures of high temperature and pressure to obtain ignition and heat release. As the scramjet configuration is scaled in size, the size of the hot pockets scales in the same way, and thus the accumulated fluid residence time in those hot pockets also scales in the same way. If p*L scaling applies, and if the pressure is scaled inversely with the geometry, then exactly the same number of hot pockets will be needed to complete combustion for each scale. If p*L scaling applies, it will be because the two-body dissociation reactions in the hot pockets dominate the influence of three-body recombination reactions in the expansion regions between the hot pockets. The usual assumption is that all reactions are in fact chemically frozen in the expansion regions, which would indeed result in successful p*L scaling. However, the detailed reaction rate analysis of McGuire et al (2008a), for a system that required two hot pockets to complete combustion, showed in the expansion region between the two hot pockets that the reactions do **not** freeze but rather the three-body recombination reactions become significant in comparison with the two-body dissociation reactions. Furthermore, the amount of heat released from those three-body reactions can increase the local temperature sufficiently that when the fluid reaches the shocks that create the second hot pocket, the post-shock temperature is high enough for explosive reaction to take place. Three-body reactions do not obey binary scaling. The important question to be answered experimentally is thus : **does the chemical behaviour of the expansion regions between the hot pockets significantly influence the overall combustion behaviour, or does p*L scaling apply to inlet-injection radical farming scramjets with sufficient accuracy to be applied to extrapolate ground test data to flight?**

To answer this key question, T4 shock tunnel tests supported by computational fluid dynamics simulations and combustion kinetics analyses have been conducted.

World best practice in high speed flow research is a close coupling between experimental and numerical approaches. In such an approach, analysis (if the configuration is simple enough) or computational fluid dynamics (CFD) is used to plan the experiments so that the right experiments are performed, and in the case of CFD to probe the detail of the experimental flowfields to provide data that is unobtainable from experimental measurement. The analysis and CFD is also used for studying trends and extracting the key underlying phenomena. The experiments however are the direct connection to reality and are the key source of data that underpins the conclusions of the research. The experiments are used to calibrate/validate the numerical methods. The research here includes both numerical (computational fluid dynamics), analytical (combustion chemical kinetics) and experimental (shock tunnel testing).

The configuration studied is a modified version of the generic 2D internal combustion chamber configuration of Odam & Paull. This configuration is the 2D analogue of the axisymmetric configuration intended for HIFiRE 3. A new model (see Figure 6) has been designed with the assistance of numerical simulations of the combustion flowfields, and fabricated such that the combustion chamber is longer, meaning that 5 hot pockets are generated along the wall. Flow conditions have been sought for which ignition takes place at the middle hot pocket, and then the pressure has been ramped up and down in order to move the ignition location upstream and downstream. Surface heat transfer and surface pressure distributions have been measured and compared with numerical reconstructions of the flowfields. From these comparisons, insight into the scaling laws for this class of scramjet are possible. The other aspect of the new test article is that it is equipped with large windows for flow visualization.

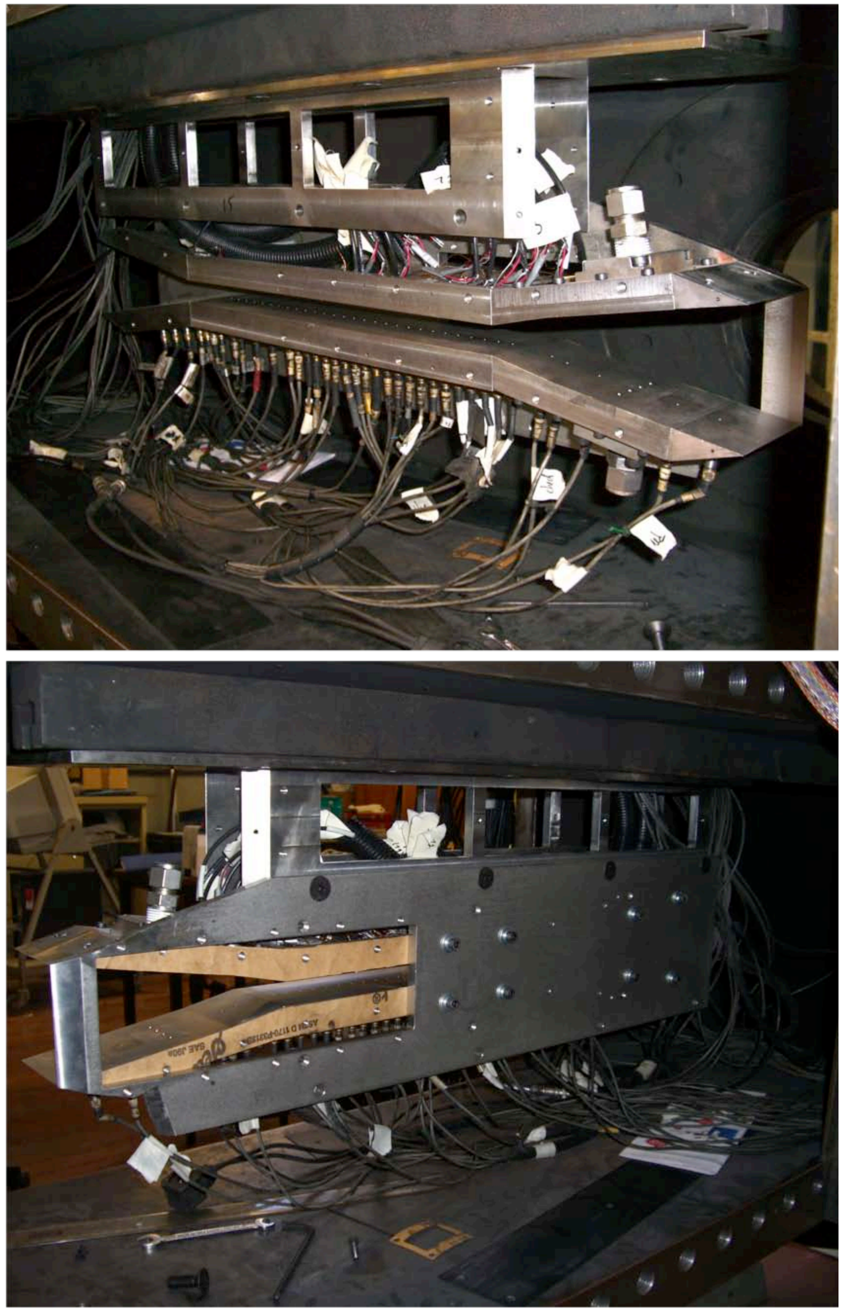


Figure 6. The present scramjet test article in the T4 shock tunnel test section.

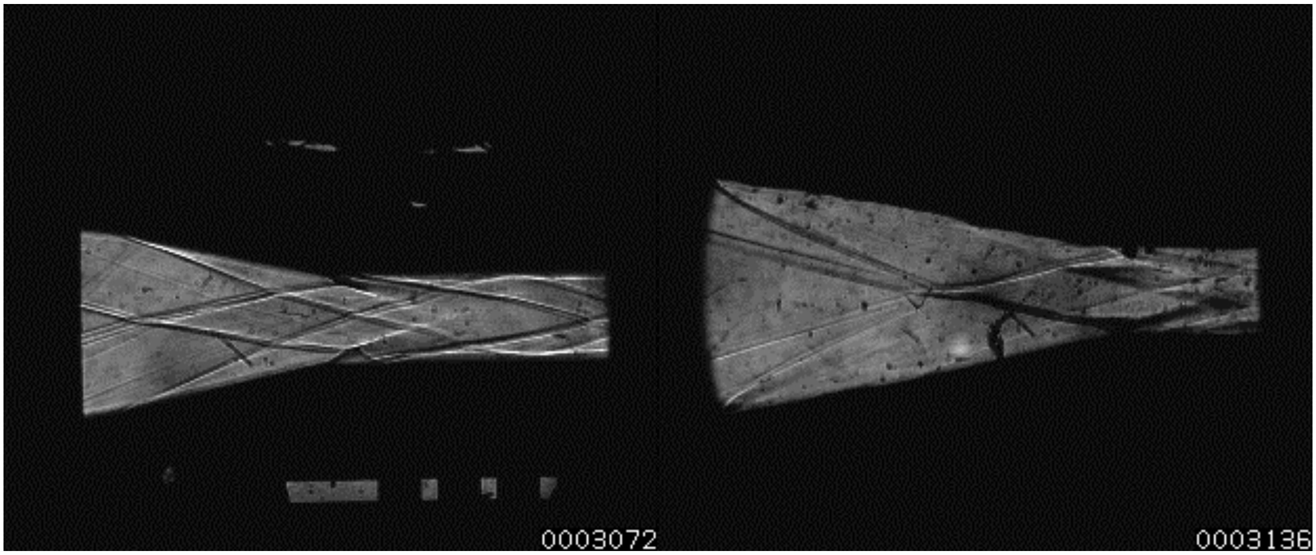


Figure 7. Schlieren visualisation of the inlet and upstream combustor flowfields. Left : fuel-off. Right : fuel-on, air.

Figure 7 above provides line-of-sight density-gradient-sensitive schlieren images captured with a high speed camera for the flow in the scramjet inlet and upstream part of the combustion chamber. The image on the left is for the fuel-off case, and shows the shock and expansion system generated by the inlet and combustion chamber entrance. Flow is from left to right. The image on the right is the fuel-on case. A modified inlet shock structure, a result of the injection of hydrogen fuel on the second inlet ramp, can be seen.

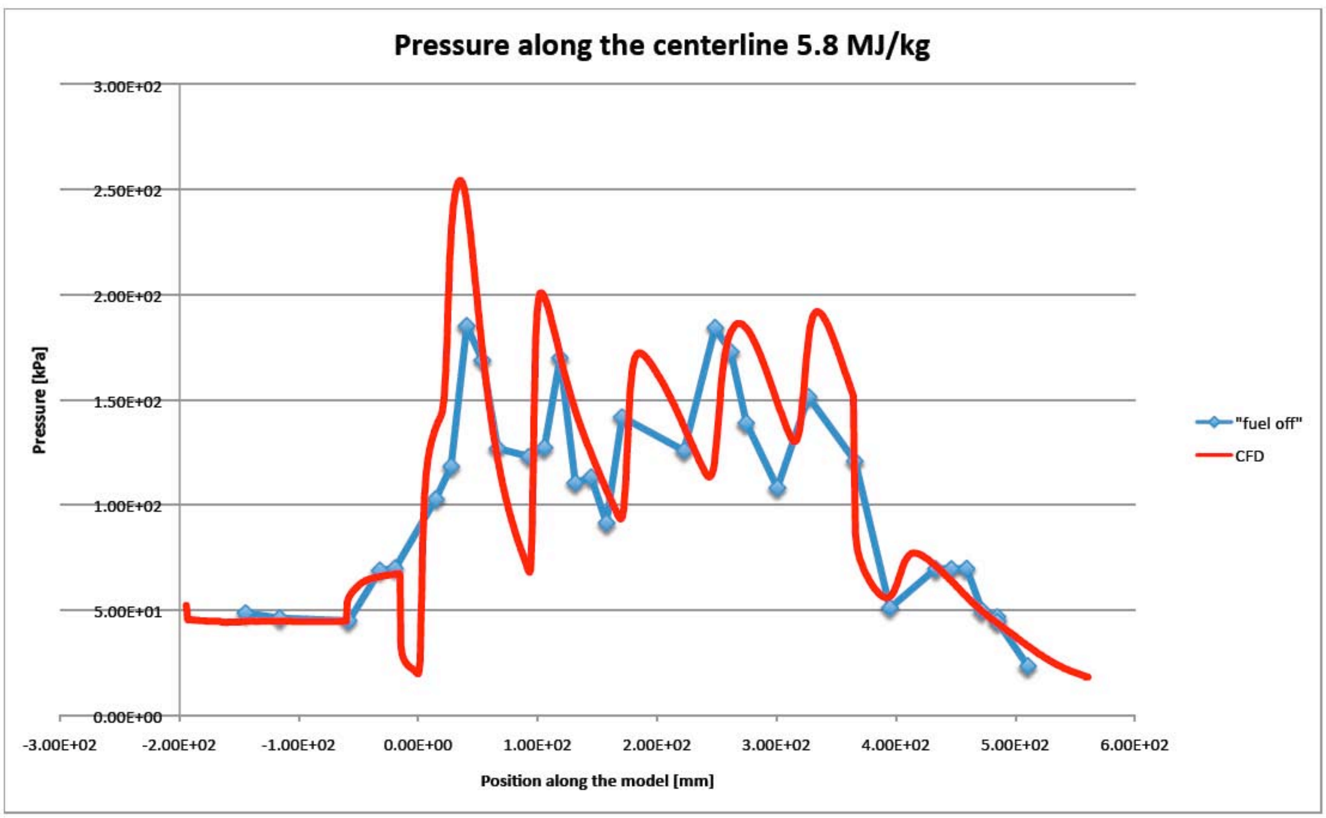


Figure 8. Comparison between experimental and CFD surface pressure distributions, fuel-off.

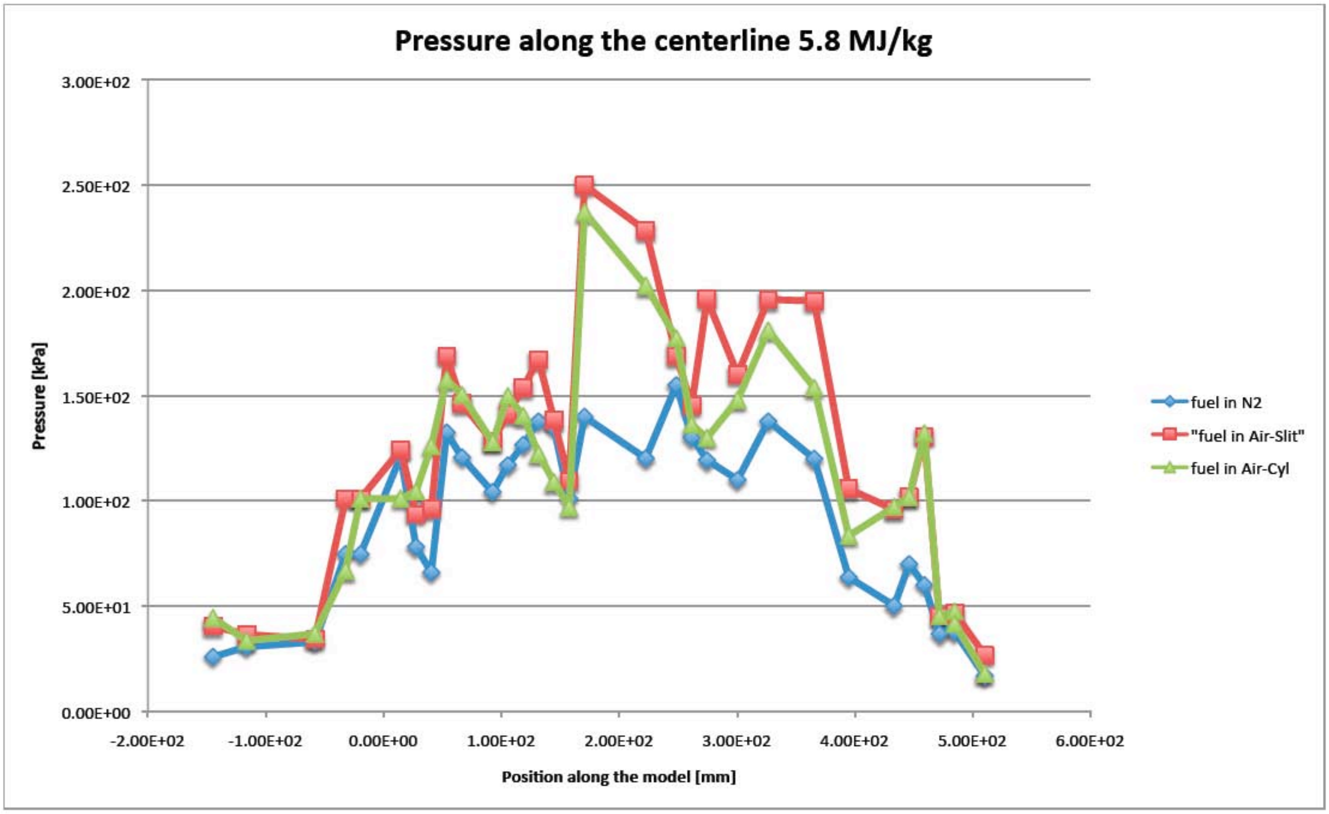


Figure 9. Comparison between experimental and CFD surface pressure distributions, fuel-on into air and nitrogen.

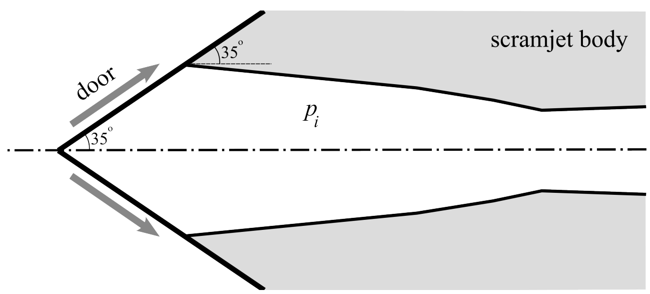
Measured surface pressures for fuel-off, fuel-on into nitrogen (to obtain mixing flowfields without combustion) and fuel-on into air are presented in Figures 8 and 9. The CFD in these cases has assumed a uniform inflow, however further simulations, for all flow conditions, are being finalised that account for the non-uniformities in the freestream flows. The experimental results are as expected, in that when the pressure is increased the ignition moves upstream, and vice versa when the pressure is decreased. From the numerical reconstructions of these flowfields, understanding of the scaling laws of this class of scramjet is being developed, and will be reported in a follow-up report.

Inlet starting.

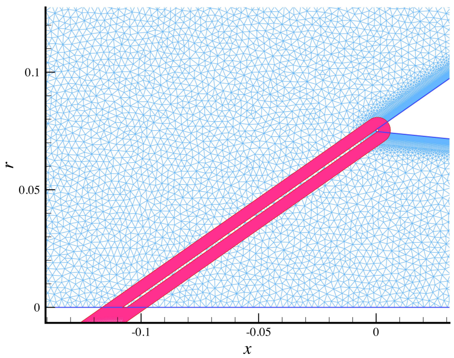
Efficient scramjet operation requires a hypersonic inlet that compresses the low pressure/temperature ambient air at high altitude to conditions of the order of 100 kPa and 1000 K. This compression is achieved by contracting the flow, and should do this with oblique shock waves that maintain supersonic flow through the inlet and into the combustion chamber. At the contraction ratios (between inlet entrance and exit) typically required, supersonic “started” flow is possible, but subsonic “unstarted” or “choked” flow with a strong normal shock wave in or upstream of the inlet is also possible. The latter is disastrous for scramjet operation.

Starting a choked hypersonic inlet can be achieved by means of variable geometry to modify the contraction ratio during flight. It can also be achieved by utilising the highly unsteady flow phenomena that occur if the scramjet is subject to enormous acceleration (as would be the case in a ballistic range flight), if a thin diaphragm protecting the inlet is ruptured (as is also the case in the ballistic range), or if an impulse facility such as a shock tunnel is used to generate the hypersonic stream. These unsteady methods are examples of impulsive starting (see for example Timofeev et al, 2008). The axisymmetric configuration considered here has been shown to start impulsively in the T4 shock tunnel. Of critical importance is whether the configuration will start in atmospheric flight, and investigation of this has been performed in this research, and has been published (Ogawa et al, 2010). Results from that publication are repeated here.

One approach examined in the present study is to attempt to satisfy the Kantrowitz criterion by directly modifying the inlet geometry and thus regulating mass flow entry. The methods tested here include opening doors and sliding doors (or diaphragm erosion). Relatively slow movement of the inlet components employed in these methods is to lead the flowfields to transition in a quasi-steady manner rather than unsteady. The configurations of these methods are based on that of diaphragm rupture and the internal pressure downstream of the solid moving part is 65% of the freestream value for both methods. One methodology is described below.



(a) schematic diagram



b) mesh close-up

Figure 11. Sliding doors (diaphragm erosion)

The inlet is initially covered by a flat door with the same dimensions as the diaphragm used in the previous section, apart from a definite thickness of 1mm. The door slides upwards at a constant velocity (Figure 11 (a)), increasing the aperture for mass flow entry, so that a fully open inlet is achieved in 50 milliseconds. The slope of the external contour of the inlet is modified to 35° in this particular case in order to accommodate the retrieving door without extrusion. This method is analogous to the erosion of a temporary conical diaphragm which gradually melts off from the tip due to the aerodynamic heat load undergone at the stagnation point. The surrounding of the door is represented by a structured mesh comprising 437×50 cells with a minimum cell width of 5×10^{-5}m at the wall (Figure 11 (b)), linked to the background mesh by an overset zonal boundary condition.

The progression of transitional flowfields induced by this method is displayed in Figure 12. Initially the inlet is completely sealed with a door fully closed at t=0ms. The external air flows into the channel as the door is retracted upwards (t≥10ms). It can be seen that the channel is constantly filled with hypersonic airflow with the same Mach number as the freestream value, that is, M_∞=8, with no presence of a shock wave observed throughout the passage. The region behind the door is dominated by stagnant fluids, which constantly diminish with the opening of the aperture and eventually disappears when the door is fully retracted (t=50ms).

The mass flow rates monitored at the entrance and exit of the inlet are plotted in Figure 13. It can be seen that the inflow and outflow rates constantly increase at the same rate, closely linked with each other with negligible difference throughout the process. This feature represents a high degree of quasi-steadiness of the flowfield. The flow rates level off at high values close to 0.8kg/s after the completion of the door motion (t>50ms), comparable to what have been seen in Figure 13 (b), indicating a successfully started inlet.

The high efficacy of this method in starting the inlet can be traced to the effective contraction ratio between the inflow and outflow, which is regulated by the variable aperture. Figure 14 shows the path of the area contraction during the process, superimposed in the Kantrowitz diagram. The area ratio between the outflow and inflow (A^*/A_i) is, in effect, higher than 1 at the early stage of the process due to the small inflow aperture (A_i), which allows to position the inlet well above the Kantrowitz limit, where the inlet starts spontaneously. As the sliding door opens, the increasing aperture brings the contraction ratio down across the Kantrowitz line into the dual solution zone, where both started and unstarted states can be possible. The inlet, which has already been started, remains operational even in this zone, leading to successful starting.

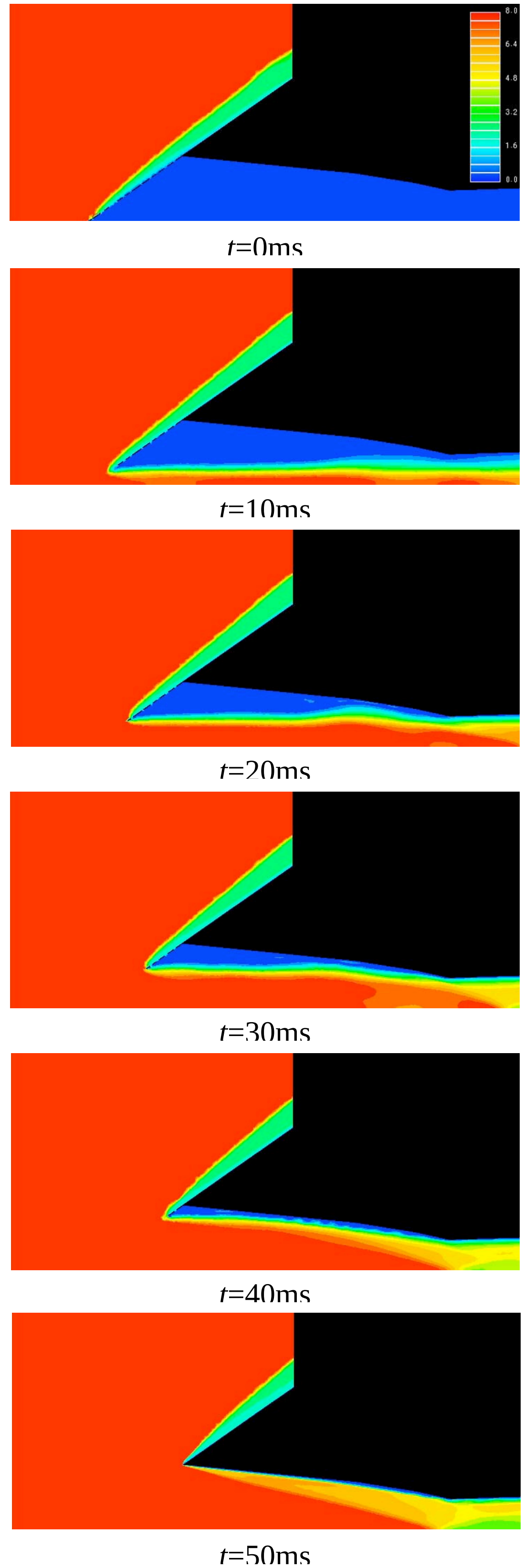


Figure 12. Transient flowfields during sliding door opening (Mach number distributions)

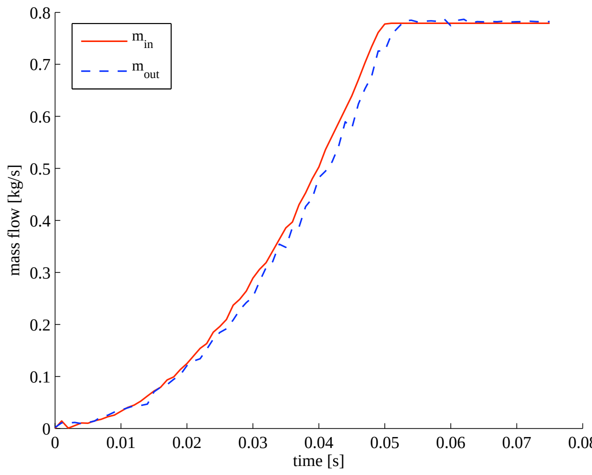


Figure 13. Mass flow rates at the inlet entrance (x=0)

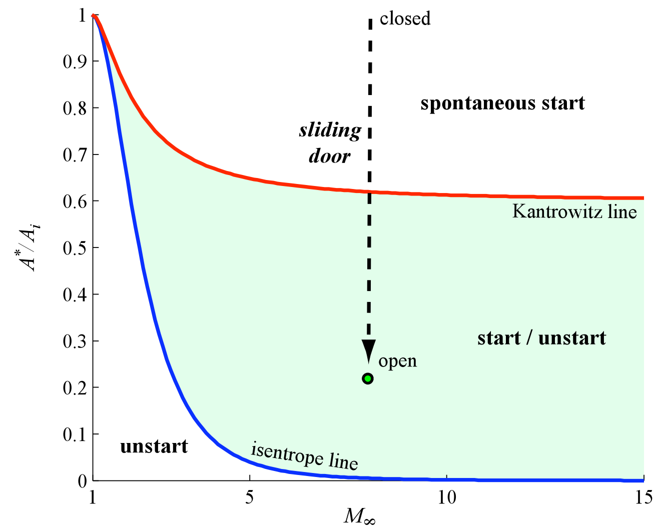


Figure 14. Sliding door process in Kantrowitz diagram

Conclusion

Experiments have been performed in the T4 shock tunnel in which an inlet-fuelled radical farming scramjet has been studied with surface pressure and heat transfer measurements and high speed schlieren flow visualisation. For given flight Mach number, conditions have been identified at which combustion ignition takes place in the middle of five hot structures in the flow, and this ignition point has been moved upstream and downstream by scaling the dynamic pressure. Numerical reconstruction of the flows enables the combustion scaling laws to be uncovered, full details of which will be provided in a follow-on report.

Numerical studies have also been conducted of novel methods for inlet starting methods for the high contraction ratio inlets used by such scramjets. The most promising method, presented here, is that of sliding doors in two dimensions or an eroding conical diaphragm in three dimensions. Such a concept has been found to quickly and efficiently start such high contraction inlets.

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